

Passively Mode-Locked Waveguide Laser With Low Residual Jitter

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Abstract—Picosecond pulses at $1.53\ \mu\text{m}$ with low residual jitter are generated from a passively mode-locked erbium/ytterbium codoped planar waveguide laser in an extended cavity configuration. The round-trip frequency of the laser cavity is actively referenced to the frequency of a stable electronic oscillator; this lowers the residual root-mean-square timing jitter to 83 fs over the frequency range of our phase-noise measurement system 100 Hz–10 MHz.

Index Terms—Erbium/ytterbium, jitter, mode-locked lasers, optical planar waveguides.

I. INTRODUCTION

COMPACT low-jitter optical pulse sources with sufficient power are critical for high-data-rate communication systems and optical sampling systems used for high-speed analog-to-digital conversion [1]. Planar waveguide lasers based on Er–Yb codoped phosphate glass can produce continuous-wave (CW) output powers that exceed 170 mW at a wavelength of $1.54\ \mu\text{m}$ [2], and we have observed averaged output powers of greater than 20 mW during CW mode-locked operation. In addition, these lasers have sufficient gain to enable laser operation with relatively short cavity lengths. This enables high-frequency mode-locked operation without the need for harmonic mode locking and its associated supermode or pattern noise problems [3]. Passively mode locking these lasers offers advantages in simplicity and in reduced intracavity loss. The cavity typically consists of a short ($\sim 2\ \text{cm}$) glass waveguide, an output-coupler mirror, and a low-loss semiconductor saturable absorber mirror (SESAM) as a mode locker [4]. No active modulator, with its associated insertion loss, is required. On the other hand, since no fixed electronic frequency reference exists, passively mode-locked lasers are less attractive for communication or sampling systems where an external electronic clock is often provided for reference. In this letter, we demonstrate that the cavity of a passively mode-locked waveguide laser can be actively phase locked to a stable electronic reference oscillator to produce an optical source with low-phase noise relative to an external electronic clock.

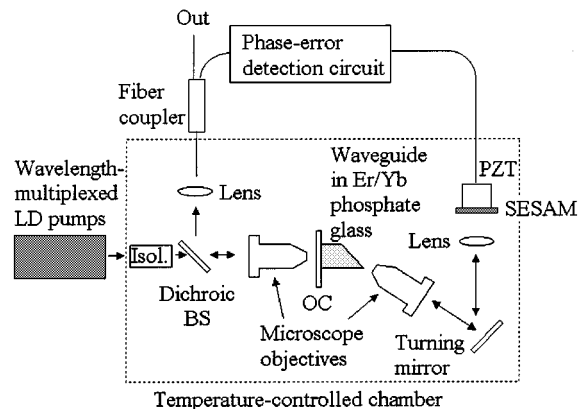


Fig. 1. Passively mode-locked Er–Yb waveguide laser configuration. LD: laser diode, Isol.: optical isolator, BS: optical beam splitter, OC: output coupler, PZT: piezo-electric transducer, SESAM: semiconductor saturable absorber mirror.

II. EXPERIMENT

The laser configuration is shown in Fig. 1. Through coupling optics and an optical isolator, wavelength-multiplexed laser diodes, near a wavelength of 977 nm, pumped a 2-cm-long waveguide positioned at one end of the laser cavity. The waveguide was fabricated in Er–Yb codoped phosphate glass [5]. A partially reflecting mirror was butted to one facet of the waveguide with index-matching fluid and served as an output coupler (OC). The other facet was cut and polished at Brewster's angle to minimize intracavity reflections in the extended cavity setup. A microscope objective collimated the light from the waveguide, and this beam was focused onto the SESAM with a second lens. The SESAM, also described elsewhere [4], [6], had a multiple quantum-well (MQW) layer made of three low-temperature-grown (LT) InGaAs–GaAs quantum wells in an antiresonant configuration on top of a 22.5-period distributed Bragg reflector (DBR) consisting of alternating AlAs–GaAs quarter-wave layers. It was mounted on a piezoelectric transducer (PZT) for active cavity-length control with a phase-error detection circuit. Although shorter cavities produced stable CW mode locking at repetition rates exceeding 920 MHz, the cavity length here, ($\sim 32\ \text{cm}$), was set to give a repetition frequency of 472 MHz, the frequency of an available electronic oscillator. An intracavity turning mirror minimized the space required for the laser and reduced the intensity of the pump light that reached the SESAM. A dichroic beamsplitter passed the 977-nm pump light and coupled the 1534-nm laser output into a single-mode optical fiber. A fiber coupler sent a portion of the laser output to the phase-error detection circuit.

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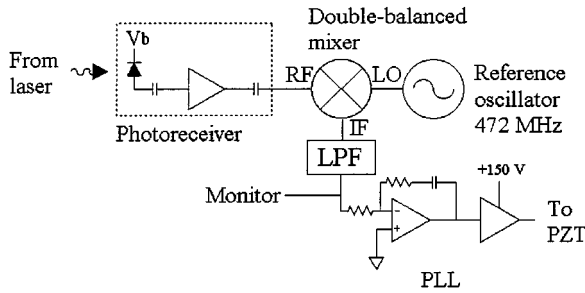


Fig. 2. Phase-error detection circuit. Vb: photodiode bias voltage, RF: radio frequency, LO: local oscillator, IF: intermediate frequency, LPF: low-pass filter, PLL: phase-locked loop, PZT: piezo electric transducer.

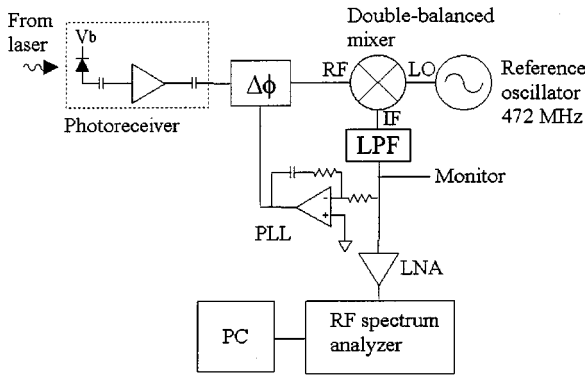


Fig. 3. Phase-noise measurement system. $\Delta\phi$: electronically controlled phase shifter, LNA: low-noise amplifier.

The laser was enclosed in a temperature-controlled chamber that was also designed to minimize the effects of vibration noise.

Fig. 2 shows the phase-error detection circuit that phased locked the repetition frequency of the laser oscillator to the electronic radio frequency (RF) reference. The circuit is similar to one employed by Walker *et al.* [7] and those used by other groups [8]. Signals from a monitor photoreceiver and the reference oscillator were fed into a double-balanced mixer to produce a phase-error signal at the intermediate frequency (IF) port. A low-pass filter (LPF) eliminated any unwanted higher frequency products. With the help of an intraloop high-voltage amplifier, a phase-locked loop (PLL) continuously adjusted the voltage on the laser's PZT to maintain quadrature between the signals of the mode-locked laser and the reference oscillator, locking the laser repetition frequency to that of the reference oscillator and reducing relative timing fluctuations.

Phase-noise measurements were made with the phase-detector method [9]–[11]. The setup, shown in Fig. 3, incorporated some of the same components found in the phase-error detection circuit of Fig. 2. Signals from a second monitor photoreceiver and the reference oscillator of Fig. 2 were fed into a double-balanced mixer to produce a voltage at the IF port that was proportional to the phase difference between the two sources. An LPF eliminated any higher frequency products. A PLL maintained quadrature between the two sources by tuning an electronically controlled phase shifter placed after the photoreceiver. This ensured maximum phase-noise sensitivity and minimum susceptibility to amplitude noise. The bandwidth of the PLL was set low enough to minimize its effect on the

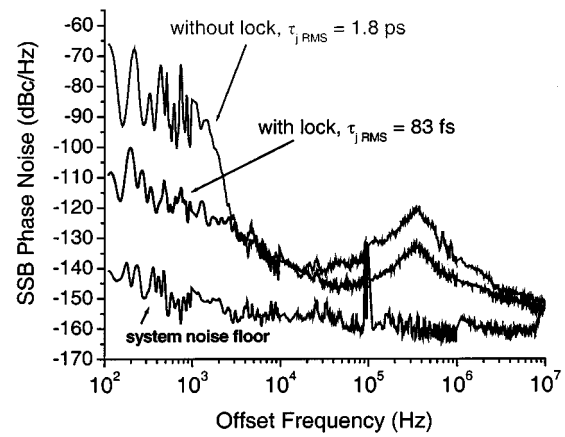


Fig. 4. Residual single-sideband phase noise of the passively mode-locked waveguide laser as a function of offset frequency from the laser repetition frequency of 472 MHz. Locking laser cavity to reference oscillator reduces residual jitter from 1.8 ps to 83 fs (100 Hz–10 MHz).

measured phase noise above 100 Hz. A low-noise amplifier (LNA) boosted the signal before it was fed into an RF spectrum analyzer. A personal computer (PC) controlled the synthesizer scan, collected the single-side-band (SSB) phase-noise data, \mathcal{L} (in decibels down from carrier per hertz bandwidth, dBc/Hz), and calculated the root-mean-square (rms) timing jitter $\tau_{j,rms}$, given the laser repetition frequency f_R , per (1) [11]

$$\tau_{j,rms} = \frac{1}{2\pi f_R} \sqrt{2 \int_{f_{min}}^{f_{max}} \mathcal{L} df}. \quad (1)$$

III. RESULTS

In the configuration of Fig. 1, the mode-locked laser produced pulses with an autocorrelation duration of 8.5-ps full-width at half-maximum (FWHM) and a spectral bandwidth of 0.65-nm FWHM centered at 1533.5 nm. Assuming a Gaussian pulse shape, the actual pulsewidth was 6-ps FWHM and the time-bandwidth product $\Delta\nu\Delta\tau$ was ~ 0.5 , indicating the presence of some pulse chirp. Average output power for this laser was 4.5 mW with an estimated launched pump power of 180 mW at 977 nm. Shorter pulse durations are possible with SESAMs that have shorter recovery times. By Beryllium doping the LT-InGaAs multiple quantum wells (MQWs) with a concentration of 10^{18} cm^{-3} [12], we reduced the SESAM 1/e recovery time from 3.7 to 2.2 ps. Waveguide lasers that were mode locked with these Be-doped SESAMs in similar extended-cavity configurations produced pulses as short as 3-ps FWHM.

Fig. 4 shows the residual SSB phase noise for the passively mode-locked laser as a function of offset frequency with and without phase lock between the laser cavity and the electronic oscillator. Significant reduction in phase noise was observed with the lock enabled for frequencies below 3 kHz, a frequency representative of the response time of the feedback loop. Additional reduction in measured phase noise was observed near 340 kHz where a noticeable relaxation-oscillation peak exists. This peak, which is also present in the amplitude-noise spectrum, may be partly due to unwanted amplitude-to-phase-noise (AM to PM) conversion within our measurement system. If so, the actual

phase noise and timing jitter is less than measured. The current system noise floor limits the phase-noise measurement capability to below 10 MHz. Integration of the curves per (1) gives an rms jitter of 1.8 ± 0.2 ps (100 Hz–10 MHz) for the laser without lock and 83 ± 12 fs (100 Hz–10 MHz) for the laser locked to the reference oscillator. Both the temperature-controlled chamber and the optical isolator after the pump lasers helped improve jitter performance. The chamber helped isolate the laser from temperature fluctuations and acoustic noise present in the lab. The isolator (a polarizer followed by a quarter-wave plate) allowed pump operation at a high-output power that was otherwise inaccessible due to the destabilizing effects of optical feedback. The resulting increase in intracavity laser power reduced laser jitter by a factor of two. We suspect that this is due to the reduced laser Q -switching instabilities that decrease with an increase in intracavity power for SESAM mode-locked lasers [13]. Previous measurements of rms timing jitter gave values exceeding 10 ps for this passively mode-locked laser without any reference lock, temperature stabilization, or pump isolation [6].

IV. CONCLUSION

We have demonstrated that actively referencing the repetition frequency of a passively mode-locked waveguide laser to the frequency of an electronic oscillator can reduce residual rms pulse timing jitter from values exceeding 1 ps to 83 fs (100 Hz–10 MHz). Both optical isolation of the laser diode pumps and environmental isolation of the laser cavity also contribute to this improved noise performance. Such a fundamentally mode-locked laser should find applications in high-data-rate communication systems and optical sampling systems where potentially compact sources of low-residual-jitter optical pulses are required. Further improvements in jitter performance are expected with the planned reduction of laser relaxation oscillations with higher pump powers, reduced intracavity loss, and possible active control of pump intensity or cavity loss. We also intend to extend the frequency range of our jitter measurements and shorten the laser cavity to make a low-noise optical pulse source with repetition frequencies exceeding 1 GHz.

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